



Short Communication

Intermediate pyrolysis of biomass energy pellets for producing sustainable liquid, gaseous and solid fuels



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HIGHLIGHTS

- Biomass energy pellets were pyrolysed to produce fuels in the Pyroformer system.
- Barley straw oil has a higher calorific value, but reduced yield and quality.
- Wood and barley straw produce similar permanent gas and char.
- The overall product energy yields are over 73% for wood and barley straw.

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ABSTRACT

This work describes the use of intermediate pyrolysis system to produce liquid, gaseous and solid fuels from pelletised wood and barley straw feedstock. Experiments were conducted in a pilot-scale system and all products were collected and analysed. The liquid products were separated into an aqueous phase and an organic phase (pyrolysis oil) under gravity. The oil yields were 34.1 wt.% and 12.0 wt.% for wood and barley straw, respectively. Analysis found that both oils were rich in heterocyclic and phenolic compounds and have heating values over 24 MJ/kg. The yields of char for both feedstocks were found to be about 30 wt.%, with heating values similar to that of typical sub-bituminous class coal. Gas yields were calculated to be approximately 20 wt.%. Studies showed that both gases had heating values similar to that of downdraft gasification producer gas. Analysis on product energy yields indicated the process efficiency was about 75%.

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1. Introduction

Biomass based fuels dominated the world energy market until middle of the 19th century, when coal and other fossil fuels become increasingly popular. Since the 20th century, just over 100 years, mass production and utilisation of fossil energy have caused a series of worldwide energy supply and global environmental and climate problems. Hence the use of sustainable energy sources has been attracting research attention over the last several decades. Compared to the use of other sustainable fuel resources, biomass has the advantage of wide availability and it can be developed everywhere in the world as a local fuel resource.

Recently, alternative thermal conversion of biomass material i.e. pyrolysis and gasification, instead of direct combustion has attracted considerable research attention. Pyrolysis is of particular

interest, as it can convert solid biomass into liquid fuel oil with the benefits of higher energy content and economical storage and transport.

There are two main classes of pyrolysis technology widely practiced, namely 'slow pyrolysis' (Apaydin-Varol et al., 2007; Şensöz, 2003) primarily for biochar production, and 'fast pyrolysis' (Gopakumar, 2012; Tsai et al., 2007) for producing liquid fuel. These two terms relate to the heating rate and residence time of the biomass, 'fast' implying high heating rate and short residence time, and 'slow' implying low heating rate and long residence time. Fast pyrolysis principally uses finely ground biomass raw material heated at a very high heating rate to about 500 °C and rapid vapour cooling to room temperature to give a yield of liquid up to 75 wt.% on a dry-feed basis. The liquid is typically referred to as pyrolysis oil (or 'bio-oil').

A number of types of pyrolysis reactor have been invented and investigated for producing biomass based pyrolysis fuels by fast pyrolysis. Fluidised bed reactors, including bubbling fluidised bed

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and circulating fluidised bed, have been the most popular type owing to their simple construction and operation, good temperature control, high heating rate and high efficiency (Bridgwater, 2012). Other types of reactor such as rotating cones and ablative reactors have also been extensively investigated. The latest technical review indicates that the liquid produced from fast pyrolysis of biomass is usually produced as a single-phase mixture with about 25–50 wt.% water content, leading to a relatively low higher heating value of 10–17 MJ/kg and poor combustibility, although these parameters are variable depending on the characteristics of initial feed material and reaction conditions (Bridgwater, 2012). A few types of feedstock pre-treatment and post-treatment methods, such as catalytic cracking (Hew et al., 2010; Xu et al., 2010) and emulsifying with diesel (Chiaromonti et al., 2003) etc., have been attempted to improve the quality of pyrolysis oil. However these always results in increased fuel processing cost, for often only modest improvements.

In recent years, screw (augur) pyrolysis reactors have been developed for the pyrolysis of biomass. This type of reactor uses augur screws to mechanically transport the biomass feedstock through a heated reactor rather than using a fluid medium. Heating rates are significantly lower than in fast pyrolysis and solids residence times much longer (of the order a few minutes), leading to the use of the term “intermediate pyrolysis”. Products are more evenly distributed between liquid, char and non-condensable gas. Gopakumar (2012) studied pyrolysis of ground pinewood feedstock (having a heating value of 18.1 MJ/kg and ash content of 0.7 wt.%) in a small-scale auger reactor at various temperatures. The author found that, at a pyrolysis temperature of 450 °C, the process gave the highest liquid yield – 50 wt.% of the feedstock. The author claimed that the liquid product had a heating value of 19.1 MJ/kg and contained 21.0 wt.% water content. The char yield was 27.5 wt.% having a heating value of 26.5 MJ/kg and containing 1.2 wt.% ash. Hassan et al. (2009) pre-treated pinewood feedstock (heating value 18.6 MJ/kg and ash content 0.46 wt.%) in NaOH solution at a temperature of 100 °C for 60 min. The feedstock was fed into a screw reactor at a feeding rate of 1 kg/h and the pyrolysis temperature was 450 °C. The author claimed that the pyrolysis liquid from this type of feedstock had a heating value up to 24.4 MJ/kg. However, there is no product yield mentioned in this work. Ingram et al. (2008) conducted experiments with samples of wood and bark from pine and oak in a small-scale augur pyrolysis reactor at a feed rate of approximately 1 kg/h. The solid residence time was controlled to 50s. The wood and bark samples produced liquid yields ranging from 42.8% to 56.3%, containing 14–26% moisture and having heating values 18.3–27.9 MJ/kg. The authors did not give the amount of pyrolysis water in the liquid phase, but emphasised that it was not possible to remove the free water by centrifugation of the pyrolysis liquid. Char yield was about 20%, with a heating value of over 30 MJ/kg. However, there was no feedstock characterisation and gaseous product analysis reported.

The process of intermediate pyrolysis has been gradually recognised since the past five years due to the technology development and significant work carried out at Aston University. One feature of intermediate pyrolysis processes is that the liquid product is often seen to separate readily into an organic and an aqueous phase. Unlike when this happens with fast pyrolysis oils, the organic phase is often seen to be of a relatively good quality in terms of viscosity and heating value. It is argued that this results from the relatively long residence time and from contact with by-product char which has a catalytic effect (Bridgwater, 2012). Recent research has started to investigate the combined effect of prolonged solid residence time and use of char for improving the pyrolysis products (Abu Bakar and Titiloye, 2013; Mahmood et al., 2013; Ouadi et al., 2013; Yang et al., 2013a,b). It is found that extended

involvement of char in the pyrolysis process can lead to an improvement to the quality of the pyrolysis liquid, i.e. lower molecular weight components in the organic fraction, and considerably lower water content in the organic fraction giving a much higher heating value that is comparable to commercial oils (Hornung and Apfelbacher, 2009; Yang et al., 2013a).

Prior to the recent work, limited research has been published regarding the pyrolysis of biomass in pilot scale screw reactors, particularly in terms of the energy yields. This work presents the experiments carried out on a 20 kg/h pilot-scale Pyroformer intermediate pyrolysis reactor, using commercial wood and barley straw pellets as feedstock. The yields of pyrolysis products are presented, and all products, namely pyrolysis oil, permanent gases and char, are characterised. The mass balance and product energy yields are also determined and evaluated.

2. Methods

2.1. Feedstock

The wood pellets and barley straw pellets feedstocks used in this work were purchased from UK suppliers (Country Wide Farmers and Straw Pellets Ltd.). The wood pellets are pressed pine wood and consist of wood residues, such as sawdust and off-cuts, and have a nominal particle diameter of 6 mm and length of 15–25 mm. The barley straw pellets are produced from waste barley straw residues and they have similar dimensions to the wood pellets.

The proximate analysis and ultimate analysis of the wood and barley straw pellets are shown in Table 1. The analysis shows that the carbon, hydrogen and nitrogen contents of wood pellets and barley straw pellets are similar, but wood pellets have relatively higher volatiles. It is worth noting that the barley straw pellets contain nearly twice as much ash as wood pellets (6 wt.% for barley straw compared with 3.6 wt.% for wood). Ash in the feedstock can seriously affect the yield and characteristics of char, and is considered undesirable in the feedstock (Mayer et al., 2012).

2.2. Intermediate pyrolysis system

The Pyroformer intermediate pyrolysis reactor was designed and patented at Aston University. The reactor is an auger screw reactor, comprising a horizontal carbon steel vessel containing two co-axial rotating screws. During operation, the inner screw conveys a mixture of fresh feedstock and recycled char product forward through the reactor, and the outer screw returns a portion of the char product backwards for recycle. The solids residence time is a few minutes (disregarding the recycled char). Each of the screws is driven by an electric motor. Five electric heating jackets are attached along the length of reactor outer wall to provide the reaction temperature. The reactor has one inlet for biomass feeding, one inlet for nitrogen gas purge, one outlet for solid product (char) and one outlet for pyrolysis vapours. The Pyroformer unit is 180 cm in length and has a diameter of 20 cm. It can process a maximum of 20 kg/h of biomass feed.

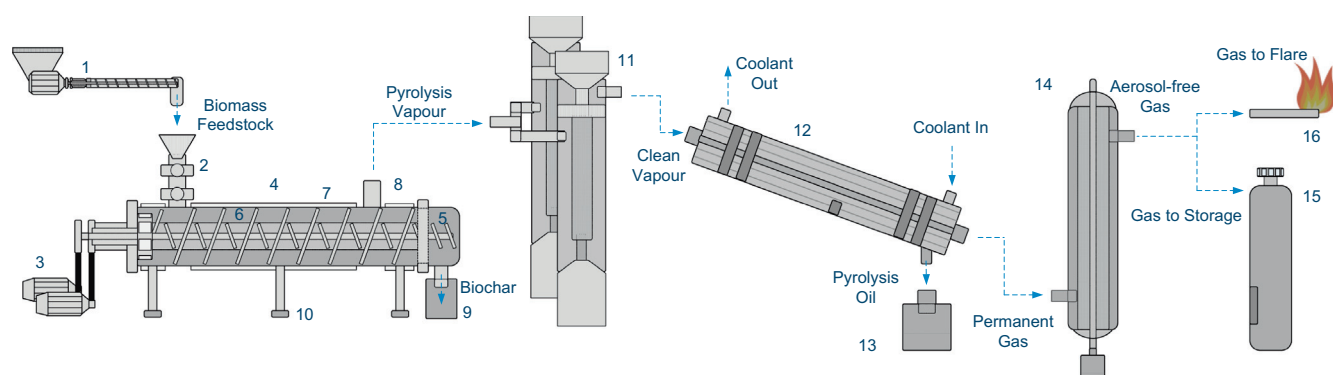
The novel feature of this reactor is the use of internal char recycling. The hot recycled char acts both as heat carrier and as catalytic cracking medium, thereby maintaining the desired temperature environment for pyrolysis and enhancing the secondary cracking reactions for pyrolysis vapours, so as to produce a greater fraction of permanent fuel gases (H₂ and CO) and lower molecular weight condensable organics and less heavy tars, as will be discussed later.

The Pyroformer unit and full intermediate pyrolysis system is shown in Fig. 1. The system comprises a screw feeder, the

Table 1
Feedstock and products analysis.

		Unit	Wood	Barley straw
<i>Feedstocks analysis</i>				
Ultimate analysis	C	wt.%	47.5	44.2
	H	wt.%	5.3	6.1
	N	wt.%	0.4	0.4
	O*	wt.%	36.4	30.4
	S	wt.%	<0.1	0.6
Proximate analysis	Cl	wt.%	<0.1	0.4
	Volatile matter	wt.%	82.1	74.9
	Moisture	wt.%	7.0	11.9
	Fixed carbon	wt.%	7.7	7.2
	Ash	wt.%	3.2	6.0
HHV		MJ/kg	18.2	17.0
<i>Pyrolysis oil analysis</i>				
Elemental analysis	C	wt.%	55.69	62.57
	H	wt.%	7.93	8.12
	N	wt.%	0.36	1.41
	O*	wt.%	36.02	25.79
	TAN	g/mgKOH	47.5	30.9
Properties	Moisture	wt.%	15.4	5.8
	HHV	MJ/kg	24.2	28.9
	Kinematic viscosity @ 40 °C	cSt	14.8	30.5
	Density @ 20 °C	g/ml	1.10	1.15
	Carbon residue	wt.%	3.55	6.50
	Ash	wt.%	0.18	0.20
<i>Gas analysis</i>				
Components	H ₂	%	2.24	1.54
	O ₂	%	–	0.42
	N ₂	%	5.54	4.68
	CO	%	34.70	21.74
	CH ₄	%	7.24	10.48
	CO ₂	%	50.27	60.13
	HHV	MJ/m ³	7.27	6.92
<i>Char analysis</i>				
Elemental analysis	C	wt.%	75.60	74.83
	H	wt.%	3.38	3.51
	N	wt.%	0.22	0.10
	O*	wt.%	10.20	8.46
	Ash	wt.%	10.60	13.10
HHV		MJ/kg	30.1	32.9

* Calculated by difference.

**Fig. 1.** Schematic diagram of the intermediate pyrolysis system. (1) Feeding system; (2) feed inlet; (3) electric motors; (4) the Pyroformer; (5) inner screw; (6) outer screw; (7) external heating jackets; (8) vapour outlet; (9) char pot; (10) stands; (11) hot gas filter; (12) shell and tube condenser; (13) oil vessel; (14) electrostatic precipitator; (15) gas vessel; (16) gas flare.

Pyroformer reactor, hot gas filter candles, a shell and tube water cooled condenser and an electrostatic precipitator (ESP). The screw feeder continuously feeds fresh biomass through an evacuation-valve-controlled feeding chute into the Pyroformer. The pyrolysis vapour leaves the reactor and passes through hot gas filter candles which remove most of any entrained char and ash particulates from the hot vapour. After this, most of the filtered vapour is

condensed in the heat exchanger to form pyrolysis liquid, and the non-condensable permanent gases together with some aerosols pass to the ESP for aerosol removal. The final clean gas is sampled for analysis. Char from the Pyroformer is collected in a char pot, and both this and the pyrolysis liquid are also sampled for analysis. The electricity consumption for the pilot-scale Pyroformer is estimated to be 2.5 kW for a feed rate of 5 hg/h.

2.3. Processing conditions

Before the experiment, the Pyroformer reactor and hot gas filter were both gradually heated to 450 °C and held at that temperature for 30 min. The full heating up process took about 2 h. The rotating screws were also turned on during the heating up phase and the speed of the inner screw and outer screw were set to 1 rpm and 7 rpm, respectively. This gave a solid residence time of approximately 1.5 min and a char/biomass mixing ratio of 1.4. N₂ purge was used to eliminate any presence of oxygen in the heating up stage. The feed rates of the wood pellets and barley straw pellets were set to 6 kg/h and 5 kg/h, respectively. The Pyroformer feeding system was not able to achieve a full load using these feedstocks, as the bulk densities of the wood and barely pellets are relatively low and attempts to feed at higher rates resulted in feeder blockages. Liquid product generally started to appear in the liquid collecting vessel approximately 10 min after the feed commencing. N₂ purge was terminated as soon as this happened. The process then took approximately one hour to reach steady state (constant temperature and char production rate), after which steady state conditions were maintained for a minimum of one hour. 10–12 kg of feedstock was used for each run.

2.4. Product characterisation

Proximate and ultimate analysis of the feedstock and CHN analysis of the pyrolysis oil and char were conducted by Medac Ltd. and Marchwood Scientific Services Ltd.

GC/MS (gas chromatography and mass spectrometry) was used to analyse the molecular composition of the pyrolysis oils. A HP 5890 Series II plus Gas Chromatograph and a HP 5972 Series Mass Selective Detector were used. Oil samples were dissolved in chloroform (HPLC grade) at 1:10 sample-solvent ratio. An Agilent J&W DB 1701 Capillary Column (60 m × 0.25 mm i.d.; film thickness 0.25 µm) was used in the GC. Helium was used as the carrier gas (flow rate 1.5 ml/min). The oven heating profile was pre-programmed at an initial temperature of 40 °C and ramped to 290 °C, at a rate of increase of 3 °C/min. Final temperature was maintained for 20 min. Sample initial injection temperature was 310 °C. The mass spectra obtained from the MS detector were then processed by MassFinder 4 software where the major peaks of the chromatograph were integrated and identified according to the NIST mass library.

Analysis of permanent gas samples was carried out using a Thermal Conductivity Detector (GC/TCD) in a Hewlett Packard HP-5890 Series II GC device. An Agilent J&W a 60/80 Carboxen-1000 column (3.05 m × 2 mm i.d.) was used. Oven heating profile was set to an increase rate of 20 °C/min, from a temperature of 35–225 °C. Helium was used as the carrier gas at a flow rate of 30 ml/min. The HHV (higher heating value) of the permanent gas at the standard state of 101.3 kPa and 273 K was estimated from the gas composition by:

$$\text{HHV} = (12.776[\text{H}_2] + 12.644[\text{CO}] + 39.847[\text{CH}_4] + 63.438[\text{C}_2\text{H}_4] + \dots)/100$$

where the gas content is given in vol.% (or mol.%). The heat of combustion is in MJ/Nm³. The equation is based on heat of combustion data, assuming ideal-gas behaviour for the gaseous species (Haynes, 2013).

For pyrolysis oil analysis, the HHV was measured by a Parr 6100 calorimeter in accordance with ASTM D420. Density was measured by a Mettler Toledo 30PX densitometer. Kinematic viscosity was measured in accordance with ASTM D445 by Cannon-Fenske Routine glass capillary viscometers immersed in a 40 °C water bath. Moisture content of the pyrolysis oil was determined by the use

of Mettler Toledo V30 Compact Volumetric Karl Fischer (KF) titrator in accordance with ASTM E203, using HYDRANAL Working Medium K as a solvent and HYDRANAL Karl Fischer Composite 5 as a titrant. Total acid number (TAN) of the pyrolysis oil was measured in accordance with ASTM D664 by using a Mettler Toledo V20 Compact titrator, using standard titration solvent (toluene: 2-propanol: H₂O, 0.5: 0.495: 0.005) and Potassium hydroxide solution 0.1 M (0.1 N) in alcohol as a titrant. Conradson Carbon Residue (CCR) was measured in accordance with ASTM D189 by manual method. Ash content of pyrolysis oil and char was determined based on the ASTM D482 standard using a Carbolite AAF ashing furnace.

The product energy yields were calculated based on the mass flow of each individual product multiplies its energy content.

3. Results and discussions

3.1. Product yields

Analysis showed that the pyrolysis liquid was the most abundant product accounting for 54.3 wt.% and 49.0 wt.% of the total for wood and barley straw, respectively. Intermediate pyrolysis liquid is generally produced with separated organic and aqueous phases. Completed separation can be seen within a few hours of the test completing. The organic phases of both wood pyrolysis liquid and barley straw pyrolysis liquid have higher densities than water, hence appeared as the bottom phase.

The pyrolysis oil (organic phase) samples were obtained using a separating funnel. It is found that 34.1 wt.% of the wood pyrolysis liquid forms pyrolysis oil, but only 12.0 wt.% for barley straw. The rest of liquid fraction is separated as an aqueous phase (light brown colour). The char yields were 28.5 wt.% and 30.1 wt.% for wood and barley straw, respectively. Yields of permanent gas were calculated by difference, which were 17.7 wt.% and 20.9 wt.% for wood and barley straw, respectively.

3.2. Oil analysis

The characteristics of the pyrolysis oils are given in Table 1. Elemental analysis shows that the wood pyrolysis oil contains less carbon and hydrogen (55.69% and 7.93%) than barley straw pyrolysis oil (62.57% and 8.12%). A higher content of carbon and hydrogen will result in higher combustion energy, as shown by the HHV analysis (barley straw oil 28.9 MJ/kg compared to wood oil 24.2 MJ/kg). Nitrogen contents of 0.36% and 1.41% are found in wood and barley straw oil, respectively in the forms of nitrous compounds in wood oil and nitrile compounds in barley straw oil. Sulphur content in the oils was not measured since sulphur content in the feedstock was very low (see Table 1).

The wood oil contains approximately three times more moisture than the barley straw oil (15.4 wt.% compared to 5.8 wt.%). This can, to some extent, explain the wood oil containing less carbon, but more oxygen than the barley straw oil. Unlike fossil fuels, which generally require minimal moisture content, some moisture is important in pyrolysis oil to reduce viscosity and aid atomisation. The wood oil viscosity is 14.8 cSt, lower than the barley straw oil at 30.5 cSt. The TAN of wood oil (47.5 g/mgKOH) is found to be higher than that of barley straw oil (30.9 g/mgKOH), as more organic acidic compounds were found in wood oil. It is worth noting that moisture in the oils plays an important role here. Higher moisture content can reduce the oil viscosity, but may also lead to higher content of water-soluble acidic components. The carbon residue of barley straw oil is nearly twice that of wood oil (6.50% compared to 3.55%). This is consistent with the greater proportion of heavy organics in the barley straw oil and corresponds the

Table 2
Compounds of the oils.

Compound	Wood (%)	Barley straw (%)
Furanic	16.94	1.62
Phenolic	67.43	30.68
Aromatic hydrocarbons	–	13.52
Cyclopentenone based compounds	7.54	8.09
Other heterocyclic	–	7.80
Organic acids	2.93	–
Long-chain hydrocarbon based compounds (including chloride and nitrile)	–	18.15
Other and unknown	5.16	20.15

physical appearance of the oils. The wood oil appears to be slightly heterogeneous, as the moisture contained is not completely miscible. Barley straw oil is more bituminous, due to the seen heavy viscous fraction of organics.

Compositional analysis indicates that the content of wood oil and barley straw oil are similar to that of fossil fuels, which mainly contain paraffins, naphthenes and aromatics (see [Table 2](#) and [Supplementary Data](#)). For wood oil, aromatic compounds are the major constituents represented by 67.43% of phenolic compounds and 16.94% of Furanic compounds. The presence of these compounds was attributable to biopolymer textures of the biomass feedstocks, especially lignin, which is composed of mainly polymerised aromatics. Following are 7.54% heterocyclic compounds and 5.38% organic acids. Furans, phenols and cyclopentenone are all flammable organics. This could ensure the oils have a good combustibility for using as energy fuels. Barley straw oil is found to be more complex than wood oil, as more types of organic compound with longer carbon chains up to C16 are detected. Apart from cyclic-organic compounds, barley straw oil also contains 18.15% of long-chain hydrocarbon based chloride and nitrile compounds. Long-chain aliphatic compounds may be derived from the decomposition of polymeric carbohydrate compounds in the biomass celluloses, and as fuel components, they can provide better combustion characteristic than aromatics, however, the presence of chloride and nitrogen elements gives concerns relating to hazardous combustion emission. It is worth noting that the barley straw oil contains up to 20.15% of unknown and other type of organics that were identified by the GC/MS analysis. This can be some complex heavy organic fraction causing the bituminous appearance of the oil. This also raises concerns for the aging of barley straw oil over long periods of storage.

3.3. Gas analysis

The results of the permanent gas analysis are also presented in [Table 1](#) (and [Supplementary Data](#)). These show that the permanent gases consist predominantly of six of gases, namely H₂, O₂, N₂, CO, CH₄ and CO₂. H₂O was not analysed here, as most of water has been condensed to form pyrolysis liquid in the condensation stage and the remainder in the gas has been removed with aerosols at the ESP stage.

Although having a similar content of gas, the formation of the pyrolysis permanent gas is completely different from that of gasification producer gas. In pyrolysis, the feedstock is heated in the absence of air (oxygen), hence there is no oxidation–reduction reaction taking place. Permanent gases are formed in primary biomass decomposition and secondary cracking and related reforming reactions. It has been reported that CO₂ formation is mainly due to the primary pyrolysis of cellulose and hemicellulose. Formation of CO is mostly during the secondary pyrolysis stage, while lignin is mainly responsible for producing CH₄ ([Yang et al., 2007](#)). Analysis shows that CO₂ is the most abundant component and it counts for

over 50% in both gases. Next is the combustible fraction, mostly CO and CH₄, 44.18% for wood gas and 33.76% for barley straw gas, representing calculated heating values of 7.27 and 6.92 MJ/m³, respectively. These values are comparable to the HHV of typical gasification syngas, which is generally between 4 and 10 MJ/Nm ([Ruiz et al., 2013](#)). It is worth noting that small amounts of H₂ are detected in both samples (2.24% and 1.54% for wood gas and barley straw gas). Generally, the content of H₂ is not expected in traditional pyrolysis gas, since no reduction process for H₂ formation occurs. In the Pyroformer, however, hot char is recycled all the time. Contact with water vapour can lead to reaction to form CO and H₂ in a heated environment.

The permanent gas normally does not contain N₂, as pyrolysis is air-free and N₂ is unlikely to be produced during pyrolysis. A small amount of N₂ is detected here, this is because there is air leakage into the reactor from the feeding system. A small leakage is unavoidable, as feedstock pellets are continuously feed into the reactor. Air enters the reactor along with the biomass, causing some pyrolysis vapour combustion and leaving N₂ in the gas phase. Minimisation of air leakage from the feeding device is an important target for the development of the Pyroformer reactor.

The pyrolysis permanent gas has a satisfactory content of combustible fraction and energy content. Hence it can be a good potential as gaseous fuel. Furthermore, researchers have reported that gas post-treatments, such as post catalytic reforming ([Mahmood et al., 2013](#)) have been effective to improve the heating value of the permanent gas. This also indicates a route for further upgrading of the gases as high quality syngas.

3.4. Char analysis

The char analysis is also presented in [Table 1](#). It shows that the wood char contains 75.60% carbon and has a heating value of 30.1 MJ/kg and barley straw char contains 74.83% carbon and has a heating value of 32.9 MJ/kg. These compare well to typical sub-bituminous class coal which contains at least 73.9% carbon and has a heating value of 29.05 MJ/kg ([Kabe et al., 2004](#)). As previously discussed, prolonged residence time promotes the secondary cracking reaction and leads to coke formation, leading to a high fraction of carbon in the char product. However, it is also noticed that the both samples contain high contents of ash (over 10%).

Compared to wood and barley straw, the pyrolysis chars can be a better energy fuel, as they do not contain moisture and have a higher heating value. The char has been volatilised and hence will give less smoke emissions when combusted.

3.5. Mass balance and energy flow

The mass balance and energy yields for wood and barley straw are shown in [Table 3](#), expressed as the energy flow rate. For the mass flow, as discussed in the product yields section, the aqueous phase is the largest produced for both feedstocks, followed by char. The oil yield of wood is similar to the gas yield, but that of barley straw is much lower.

In the energy flow, it is interesting to see that about 50% of the feedstock energy content remains in the char product, but only 24.6% and 10.0% in the oils of wood and barley straw, respectively. This presents that the current setting of the system is of the greatest interest for producing chars, but the conversion rate of feedstock to pyrolysis oil is limited, particularly for barley straw. Enhancing the cracking effect of the char by optimising residence time of the feedstock and char/biomass mixing ratio may improve this, but further investigations are required. The overall energy yields are 76.5% and 73.7% for wood and barley straw, respectively, but it is noting that this does not include the energy content of the aqueous phase of the liquid product. The results imply a good

Table 3

Mass balance and energy flow.

	Mass flow (kg/h)		Energy flow (kW)	
	Wood	Barley Straw	Wood	Barley straw
Feedstock	6.00	5.00	30.33	23.61
Oil (organic phase)	1.11	0.29	7.47	2.36
Aqueous phase	2.15	2.16	–	–
Char	1.71	1.51	14.30	13.75
Gas	1.03*	1.05*	1.44	1.29
Difference	–	–	7.12*	6.21*
Difference (%)	–	–	23.5%	26.3%

* Calculated by difference.

potential of energy conversion of the liquid fuel from the feedstock. Analysis on the aqueous phase and energy consumption of the system may be carried out in future to fully close the system energy balance.

4. Conclusions

The system successfully produced intermediate pyrolysis oils, gases and chars from wood pellets and barley straw pellets. All products were characterised. The liquid, gaseous and solid product yields for both feedstocks were at approximate proportions of 50%, 20% and 30%, respectively. Yield of wood oil is nearly 3 times higher than that of barley straw oil, but the wood oil has a lower HHV. The HHVs of the gases for both feedstocks are over 6.9 MJ/Nm³, while those of char are over 30 MJ/kg. The overall energy yields are over 73% and char accounts the most, approximately 50%.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.biortech.2014.07.044>.

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